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Heat transfer characteristics of thermal energy storage system using PCM capsules: A review

A. Felix Regin*, S.C. Solanki, J.S. Saini

Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee 247 667, India

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Abstract

Thermal energy storage has recently attracted increasing interest related to thermal applications such as space and water heating, waste heat utilization, cooling and air-conditioning. Energy storage is essential whenever there is a mismatch between the supply and consumption of energy. Use of phase change material (PCM) capsules assembled as a packed bed is one of the important methods that has been proposed to achieve the objective of high storage density with higher efficiency. A proper designing of the thermal energy storage systems using PCMs requires quantitative information about heat transfer and phase change processes in PCM. This paper reviews the development of available latent heat thermal energy storage technologies. The different aspects of storage such as material, encapsulation, heat transfer, applications and new PCM technology innovation have been carried out.
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Keywords: PCM capsules; Packed bed; Thermal energy storage

Contents

*Corresponding author. Tel.: +91 98 18354268; fax: +91 1332 285 665.
E-mail address: felixregin@gmail.com (A.F. Regin).

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1. Introduction

Energy storage leads to saving of premium fuels and makes the system more cost-effective by reducing the wastage of energy. In most systems, there is a mismatch between the energy supply and consumption of energy. The energy storage can even out this imbalance and thereby helps in saving of capital costs. It is desirable for more effective and environmentally benign energy use. Thermal energy storage is perhaps as old as civilization itself. Since recorded time, people have harvested ice and stored it for later use. A variety of thermal energy storage techniques have been developed over the past four to five decades.

Increasing energy demands, shortages of fossil fuels, and concerns over environmental impact have provided impetus to the development of renewable energy sources. Solar energy, a major renewable energy resource, is of intermittent nature and its effective utilization is in part dependent on efficient and effective energy storage systems. If no energy storage is used in solar energy systems, the major part of the energy demand will be met by the back-up or auxiliary energy and therefore the annual solar load fraction will be very low. The thermal energy can be stored when energy is abundantly available, and used as and when required. However, it is clear that if solar energy is to become an important energy source, efficient, economical and reliable solar thermal energy storage devices and methods will have to be developed.

The thermal energy storage systems can be sensible heat storage or latent heat storage, or combination of both. In the sensible heat storage, the temperature of the storage material increases as the energy is stored while the latent heat storage makes use of the energy stored when a substance changes from one phase to another. Fig. 1 shows the increase of internal energy when energy in the form of heat is added to a substance. The well-known consequence is an increase in temperature (sensible heating) or change of phase (latent heating). Starting with an initial solid state at point A, heat addition to the substance first causes sensible heating of the solid (region A–B) followed by a solid–solid phase change by crystalline structure change (region B–C), again sensible heating of the solid (region C–D), solid–liquid phase change (region D–E), sensible heating of the liquid (region E–F), liquid–gas phase change (region F–G) and sensible heating of the gas (region G–H).

The total amount of energy stored can be written as

$$Q = m\left[\int_{T_\mathrm{A}}^{T_\mathrm{D}} C_{ps}(T)\,\mathrm{d}T + L_\mathrm{p} + L + \int_{T_\mathrm{E}}^{T_\mathrm{F}} C_{pl}(T)\,\mathrm{d}T + L_\mathrm{g} + \int_{T_\mathrm{G}}^{T_\mathrm{H}} C_{pg}(T)\,\mathrm{d}T\right], \tag{1}$$

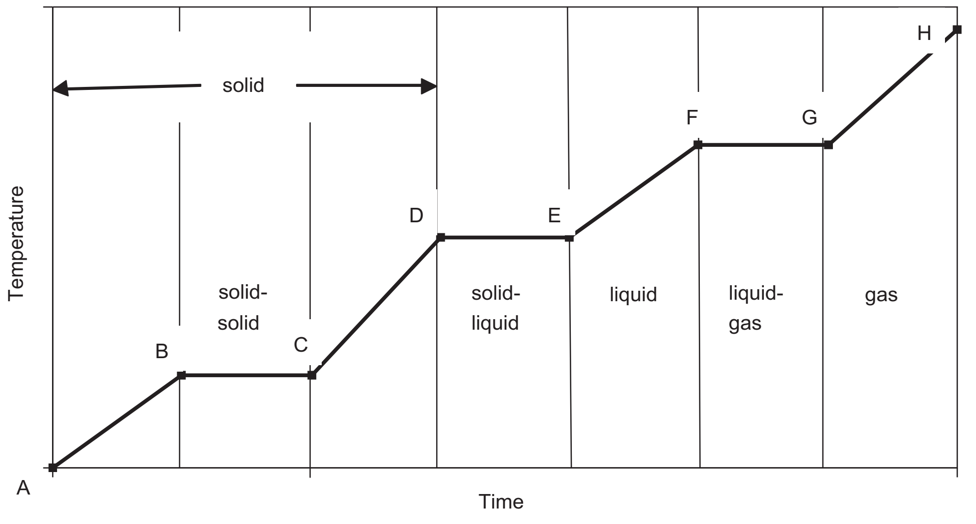


Fig. 1. Temperature–time diagram for the heating of a substance.

where m is the mass of material, C_{ps} specific heat of material in solid phase, C_{pl} specific heat of material in liquid phase, C_{pg} specific heat of material in gas phase, L_p is latent heat of solid–solid phase change, L is latent heat of solid–liquid phase change and L_g is the latent heat of liquid–gas phase change.

The storage capacity of the material depends on both its specific heat and latent heat values. Thus, it is desirable for the storage medium to have high specific heat capacity and latent heat value. Latent heat storage may be classified on the basis of the phase change process as solid–solid, solid–liquid, solid–gas and liquid–gas.

Solid–gas and liquid–gas transformations are generally not employed for energy storage in spite of their highest latent heats, since gases occupy large volumes. Large changes in volume make the system large, complex and impractical. In solid–solid transitions, heat stored as the material is transformed from one crystalline form to another. These transitions generally have small latent heats making such materials less desirable. Latent heat storage by solid–liquid phase transition is a particularly attractive technique, since it provides a high energy storage density and has the capacity to store energy as latent heat of fusion at a constant temperature corresponding to the phase transition temperature of the phase change materials (PCMs) [1,2]. This means that much smaller weight and volume of material is needed to store a certain amount of energy when phase change energy storage is used. This fact is illustrated in Table 1. Paraffin wax (as solid–liquid PCM) of mass 20.513 kg can store/release 5000 kJ of energy at its melting point (59.9 °C by assuming its initial temperature of 35 °C. To store the same amount of energy, other sensible heat storage medium would have to be heated much higher temperatures as shown in Table 2.

2. Requirements of latent heat thermal energy storage

A good design of latent heat thermal energy storage requires the knowledge of PCMs and the heat exchange processes especially the melting and solidification processes in a containment.

Table 1
Comparison of various heat storage medium (stored energy = 5000 kJ, $\Delta T = 25\,^{\circ}C$)

Property	Heat storage material						
	Paraffin wax	Water	Dowtherm.A	Therminal 66	Cast iron	Rock	Concrete
Latent heat of fusion (kJ/kg)	190	*	*	*	*	*	*
Specific heat (kJ/kg K)	2.15	4.19	2.2	2.1	0.54	0.88	0.882
Density (kg/m^3)	790	1000	867	750	7200	1600	2200
Storage mass (kg)	20.513	47.73	90.91	95.24	370.37	227.27	226.76
Relative mass**	1	2.33	4.43	4.64	18.1	11.08	11.05
Storage volume (m^3)	0.02597	0.04773	0.10485	0.127	0.0514	0.142	0.1031
Relative volume**	1	1.84	4.04	4.89	1.98	5.47	3.969

*Latent heat of fusion is not of interest for sensible heat storage.
**Relative mass and volume are based on heat storage in paraffin wax.

Table 2
Temperature rise needed to store 5000 kJ of energy

Heat storage material	Temperature rise (°C)
Paraffin wax	59.9*
Water	93.17
Dowtherm A	145.8
Therminal 66	151.1
Concrete	311.4
Rock	312
Cast iron	486.4

*Melting temperature.

2.1. System components

A latent heat thermal storage system has the following three main components:

(i) a PCM suitable for the desired temperature range;
(ii) a container for the PCM (encapsulation of PCMs);
(iii) a heat exchange surface required for transferring the heat from heat source to PCM and from PCM to the heat sink.

2.2. Phase change materials

The PCMs are the energy storage materials that have considerably higher thermal energy storage densities compared to sensible heat storage materials and are able to absorb or release large quantities of energy at a constant temperature by undergoing a change of phase.

An extensive study by Lane et al. [3] considered about 20 000 substances, seeking potential PCMs melting in the range 10–90 °C. Majority of them was rejected for improper melting point, melting with decomposition, or lack of data. At this point, no materials were excluded for reasons of low heat of fusion, poor heat conductivity, unfavorable phase diagrams, high vapor pressure (other than flammability), large volume change on melting, low density, super cooling and low crystallization rate. These are shortcomings that can be tolerated or overcome if the PCM offers sufficient advantages otherwise. Among the most extensive references related with PCMs, one can cite Abhat et al. [4], Lane [3], Garg et al. [5], Husnain [1], Dincer and Rosan [2], Mohammed et al. [6,22] and Zalba et al. [7]. These contain a complete review of the type of materials that have been used, their classification, characteristics, advantages and disadvantages and the various experimental techniques used to determine the behavior of these materials in melting and solidification.

The PCMs are grouped into four categories, namely, organic, inorganic, fatty acids and commercial PCMs. Apart from the pure compounds, the eutectic mixtures of compounds can yield different phase change temperature. There is abundant information on PCMs in the literature. Table 3 presents the different substances (inorganic, organic and fatty acids) that have been studied by different researchers for their potential use as PCMs in the temperature range 25–65 °C. No material has all the optimal characteristics required for a PCM, and the selection of a PCM for a given application requires careful consideration of the properties of various substances.

The design and operation of a latent heat thermal storage is dependent upon the physical and chemical characteristics of the PCM used. The higher the energy density of the PCM, the smaller the necessary storage volume required for each proposed application. This implies a lower cost for the heat exchange structure or a greater total heat storage capacity of the system for the same overall volume. The reported results showed [1] that one cannot simply consider any available data on technical grade PCMs for designing an effective heat storage device, as thermophysical properties vary from manufacturer to manufacturer, mainly due to different level of impurities in technical grade PCMs. A large number of materials are known to melt with a high heat of fusion in any required temperature range. However, their use as heat storage material depends on the desirable thermal, physical,

Table 3
Groups of phase change materials

Organic substances		Inorganic substances		Fatty acids		Commercial PCMs	
1	Paraffin C_{13}	7	$Mn(NO_3)_2 \cdot 6H_2O$	20	Capric–lauric acid (45–55%)	28	RT25
2	1-Dodecanol	8	$CaCl_2 \cdot 6H_2O$	21	34% Mistiric acid + 66% Capric acid	29	STL27
3	Paraffin C_{18}	9	$LiNO_3 \cdot 3H_2O$	22	Vinyl stearate	30	S27
4	1-Tetradecanol	10	$Na_2SO_4 \cdot 10H_2O$	23	Capric acid	31	RT30
5	Paraffin $C_{16–28}$	11	$Na_2CO_3 \cdot 10H_2O$	24	Lauric acid	32	TH29
6	Paraffin wax	12	$CaBr_2 \cdot 6H_2O$	25	Myristic acid	33	RT40
		13	$Na_2HPO_4 \cdot 12H_2O$	26	Palmitic acid	34	RT50
		14	$Zn(NO_3)_2 \cdot 6H_2O$	27	Stearic acid	35	TH58
		15	$K_3PO_4 \cdot 7H_2O$			36	RT65
		16	$Zn(NO_3)_2 \cdot 4H_2O$				
		17	$Na_2HPO_4 \cdot 7H_2O$				
		18	$Na_2S_2O_3 \cdot 5H_2O$				
		19	$Zn(NO_3)_2 \cdot 2H_2O$				

Table 4
Main desirable characteristics of PCMs

Thermal properties	Physical properties	Chemical properties	Economic factors
Phase change temperature suitable to the desired operating range	High density	Chemical stability	Available in large quantities
High latent heat per unit mass	Low density variation during phase change	No chemical decomposition	Inexpensive
High specific heat	Little or no supercooling during freezing	Compatibility with container materials	
High thermal conductivity in both solid and liquid phases		Non-poisonous, non-inflammable and non-explosive	

chemical properties and economic factors. The main characteristics required of the PCMs are indicated in Table 4.

The methods available for determining the heat of fusion, specific heat and melting point can be classified into three groups, namely, conventional calorimetry methods, differential scanning calorimetry methods and T-history method. The differential scanning calorimeter (DSC) provides quick and reliable results in the form of Energy-Time diagrams (Thermograms) using very small quantities of the sample (1–10 mg). Evaluation of the thermograms yields rather precise values of the phase transition temperatures during melting and freezing of sample, the heat of fusion and the specific heat variation as a function of temperature. The DSC method is well developed and a lot of researchers have used this method [8–15].

3. Encapsulation of PCM

Successful utilization of PCM and heat transfer fluid depends on developing means of containment. The PCM encapsulation with different geometries of capsules has its own advantages and disadvantages.

3.1. Functions and requirements of PCM containment

PCM containment should:

(i) meet the requirements of strength, flexibility, corrosion resistance and thermal stability;
(ii) act as barrier to protect the PCM from harmful interaction with the environment;
(iii) provide sufficient surface for heat transfer;
(iv) provide structural stability and easy handling.

Types of containment studied are bulk storage in tank heat exchangers, macroencapsulation and microencapsulation. Fig. 2 shows the various schematics of containment used in latent heat thermal energy storage (LHTS) systems [16].

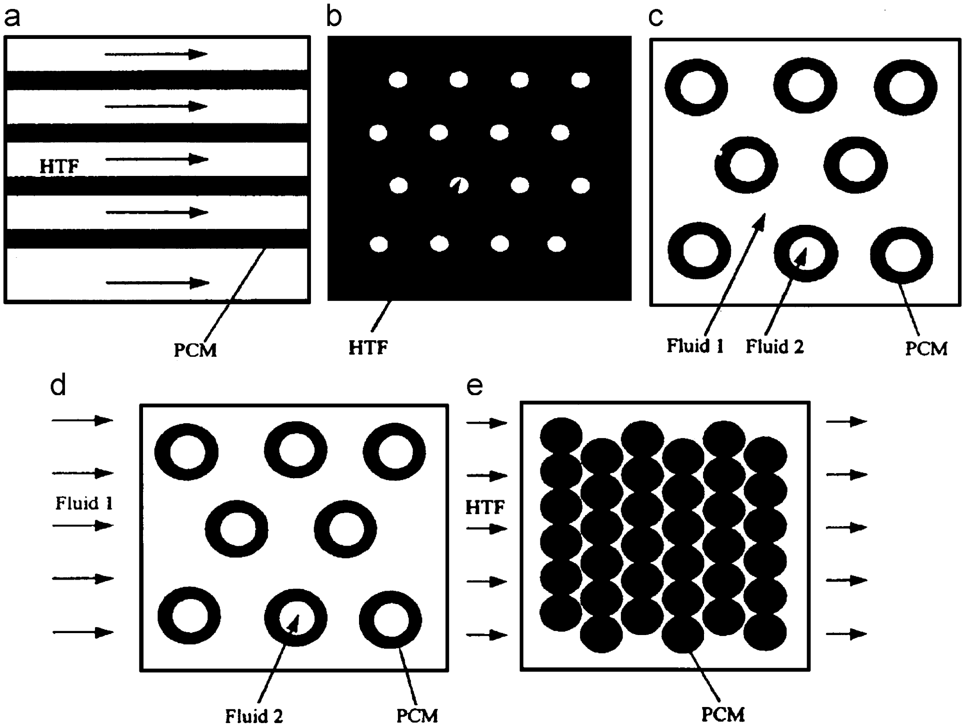


Fig. 2. Schematic of typical LHTS system [16]: (a) flat-plate; (b) shell and tube with internal flow; (c) shell and tube with parallel flow; (d) shell and tube with cross flow; (e) sphere packed bed.

3.2. Bulk storage

Bulk storage is the tank heat exchangers for PCMs are similar in design to existing tanks used for energy storage, but with some significant differences. The key unique characteristic of PCM bulk systems is the need for a more extensive heat transfer than that found in non-PCM tanks because the heat storage density of the PCM is higher compared to other storage media. The heat transfer area is lesser but it still requires a high rate of heat release or gain. The different approaches extensively used are inserting fins or using high conductivity particles, metal structures, fibers in the PCM side, direct contact heat exchangers or rolling cylinder method.

3.3. Macroencapsulation

The most common type of PCM containment is macroencapsulation in which a significant quantity of PCM is encapsulated in a discrete unit. The mass of PCM per unit may range from few grams to a kilogram. The advantage of the macroencapsulation is its applicability to both liquid and air as heat transfer fluids and easier to ship and handle. The shape of macrocapsules varies from rectangular panels to spheres to pouches without a defined shape. The key to a successful macrocapsule is to design the macrocapsule such that it fits well the intended application. The macroencapsulation of PCMs can: (i) avoid

large phase separations; (ii) increase the rate of heat transfer and (iii) provide a self-supporting structure for the PCM. The most cost-effective containers are plastic bottles (high density and low density polyethylene bottles, polypropylene bottles), tin-plated metal cans and mild steel cans. However, corrosion could lead to disastrous consequences if internal and external lacquer finishes are not applied properly to the mild steel metal cans.

3.4. Microencapsulation

Microencapsulation refers to techniques in which a large number of small PCM particles are contained within a sealed, continuous matrix. Unless the matrix encapsulating the PCM has high thermal conductivity, the microencapsulation system suffers from low heat transfer rate. The rigidity of the matrix prevents convective currents and forces all heat transfer to occur by conduction. This can reduce seriously the heat transfer rates, especially in the charging mode. Presently the cost of the microencapsulation system is high compared to other storage methods, and is used only in thermal control applications.

As evidenced by the quantity and quality of research, the macrocapsule is the dominant containment system for PCMs [17]. By careful selection of the capsule geometry and the capsule material, the macroencapsulation can be used for wide variety of energy storage needs.

3.5. Design of PCM beds for thermal energy storage

It is essential to find an efficient and economical means of achieving the heat transfer necessary to alternatively freeze and melt the storage medium in a latent heat energy storage system. The bed consists of macroencapsulated PCM, a container and the flow of heat transfer fluid through the voids in the bed. The major factors to be considered in the design of a storage unit containing a PCM include: (1) temperature limits within which the unit is to operate; (2) the melting-freezing temperature of the PCM; (3) the latent heat of the PCM; (4) the thermal load; and (5) configuration the storage bed. Other design factors which are important, but relatively less critical, are storage unit pressure drop and pumping power.

The heat is transferred to or from a heat transfer fluid as the heat transfer fluid flows through the voids in the bed. During charging mode, the hot heat transfer fluid carrying energy from the source is circulated through the tank. The PCM inside the capsules absorbs latent heat and melts. During discharging mode, cool heat transfer fluid from the load is circulated through the tank, freezing the encapsulated PCM. The heated fluid is then used to meet the load either directly or through a heat exchanger. In both operating modes (charging and discharging), the difference between the mean temperature of heat transfer fluid and the phase change temperature must be sufficient to obtain a satisfactory rate of heat transfer.

Efficient heat transfer between the fluid stream and the solid particles in the bed is required for better operation of packed bed for energy storage. There are several variables that determine the performance of a packed bed thermal energy storage unit. These variables can be divided into following three groups:

(i) Those connected with the bed construction like size, shape and packing of the material elements, bed length and the geometric configuration of the container.

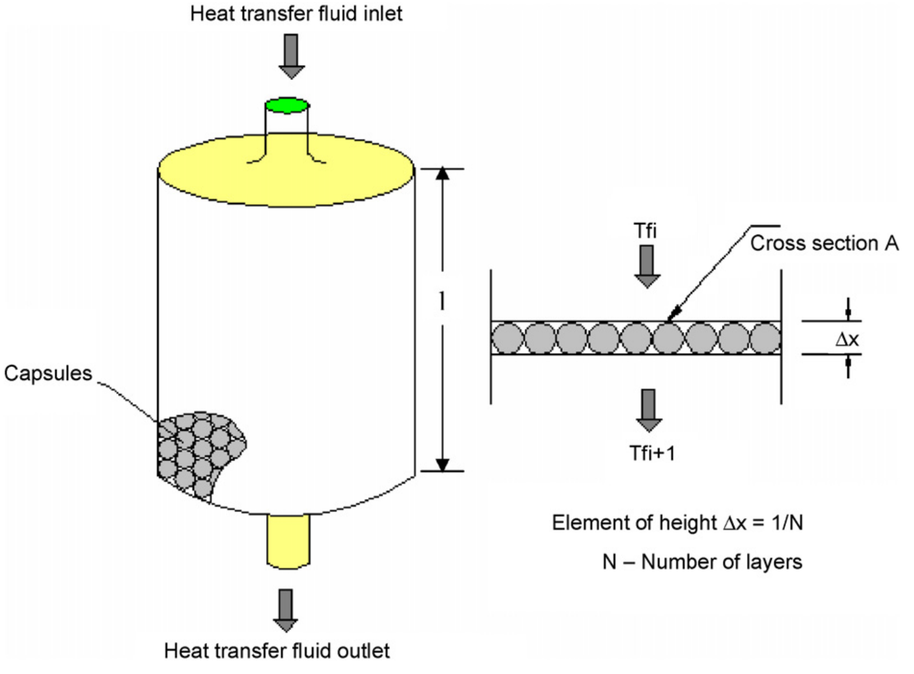


Fig. 3. Layout and details of the storage system.

(ii) Those describing the characteristics of the flowing like fluid properties and the mass velocity.
(iii) Those associated with the transient response of the bed material like initial thermal state of the bed, the inlet temperature of the fluid, the physical and thermal properties of the bed material and convective heat transfer coefficient.

In general, the principal governing parameters for design of a PCM bed are particle type, mean size and shape, void fraction within the bed, PCM and fluid thermal and transport properties, overall size of bed (cross-sectional area and length), rate of flow, and inlet temperature of the fluid. A typical LHTS unit consisting of a number of capsules arranged in a particular pattern inside container as a packed bed is shown in Fig. 3.

3.6. Design stages

The flow chart given below in Fig. 4 indicates the different stages of the development of LHTES system.

4. Heat transfer studies in packed bed system

Detailed modeling of the heat transfer and fluid flow processes that take place in such a complex arrangement of PCM capsules is quite complex. The rate of heat transfer to or from the solid in the packed bed is a function of the physical properties of the fluid and the solid, the flow rate of the fluid, and the physical characteristics of the packed bed. Pressure

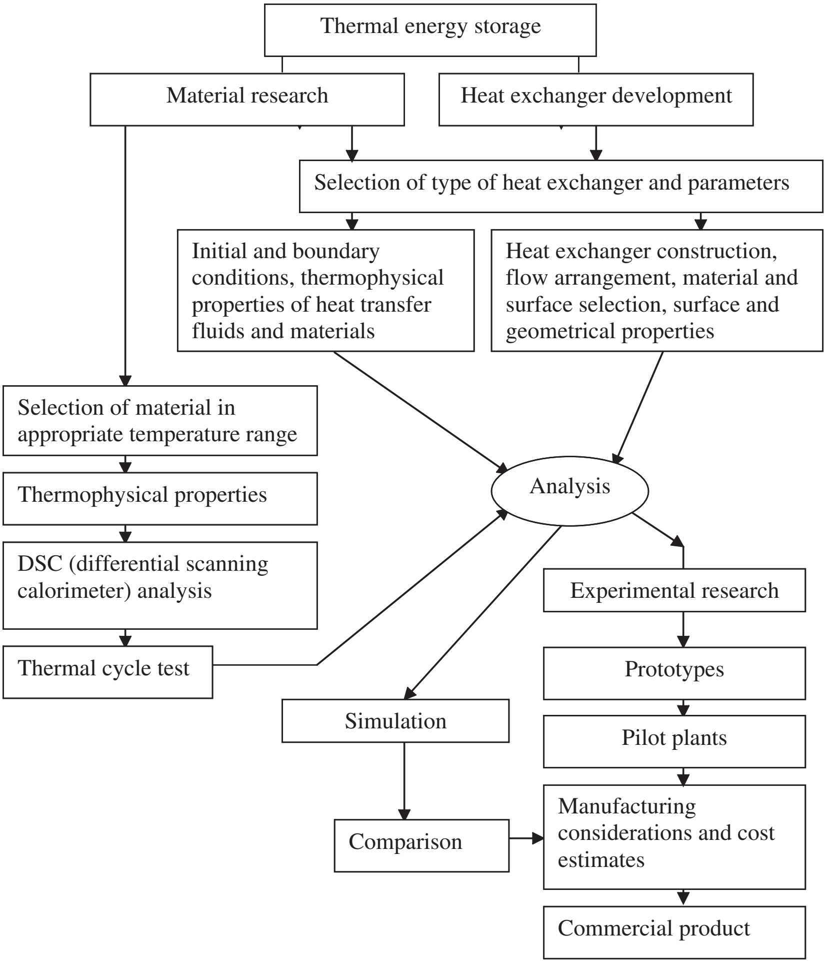


Fig. 4. Different stages involved in the design of latent heat thermal energy storage system.

drop also depends upon the flow rate of the fluid and the physical characteristics of the packed bed. Usually the shape of individual particle, voidage and specific surface area of the packing are thought to be sufficient to characterize the geometry of the packing [18].

The fluid flow phenomenon and the inter as well as intra particle heat conduction effects make the heat transfer mechanism to be complex. An extensive knowledge and thorough understanding of the heat transfer phenomenon in the bed is essential for the successful design of such systems. Balakrishnan et al. [19] reported the expected modes of heat transfer in a packed bed as: (1) the convective heat transfer from the walls of the packed bed tank to the fluid; (2) the convective heat transfer from the particles to the fluid flowing through the bed; (3) the conduction heat transfer from the walls of the bed to the particles constituting the bed; (4) the conduction heat transfer between the individual particles in the bed; (5) radiant heat transfer and (6) heat transfer by mixing of the fluid.

Two parameters, the effective conductivity and total heat transfer coefficient are commonly used to express the heat transfer rates in packed beds. The effective thermal conductivity is an averaged parameter dependent both on thermal properties of the bed and on the flow rate of heat transfer fluid [20]. The total heat transfer coefficient generally incorporates the convection between the fluid and the bed elements, conduction between the bed elements, bed to wall conduction and the fluid to wall convection [19]. Most of the experimental correlations express the heat transfer coefficient as a function of Reynolds number only. Therefore, the applicability of these correlations is also limited to a particular bed elements used in developing them. Marshall [21] mentioned that for a PCM packed bed, the overall heat transfer coefficient is a function of the mode, either heating or cooling, the state of the PCM in the capsule, i.e., fully liquid, fully solid, or melting (freezing), and lastly of the mechanism of heat transfer namely, the conduction, convection or combined conduction and convection.

In order to predict the thermal and hydrodynamic performance of a packed bed system, several mathematical models have been reported in the literature are subdivided into two major groups. The first group includes the models in which the instantaneous solid and liquid phases are the same and hence the name single phase models. The second group includes models where the bed is represented by two distinct phases: solid and fluid and hence the name two phase models. A summary of salient features of the investigations carried out in the area of heat transfer characteristics of packed bed latent heat thermal energy storage system is given in Table 5.

5. Heat transfer studies in phase change problem

The packed bed models fail to account for the thermal gradients that may prevail inside the PCM capsules. Due to the fact that most PCMs employed in commercial latent heat thermal energy storage systems have low thermal diffusivities (high Prandtl numbers), the calculated heat transfer rates between the heat transfer fluid and PCM may be inexact and, as a result, it becomes difficult to predict the thermal behavior of these systems. To overcome this limitation, one must consider the problem of heat transfer within the PCM capsule. Solid–liquid phase change (melting or solidification) heat transfer phenomena are accompanied by a phase transformation of the medium and by either absorption or release of thermal energy in the active zone. During melting, the heat exchange surface is in contact with the liquid and therefore convection is possible. During extraction of energy from storage, the liquid freezes on the heat transfer surfaces and an immobile layer of solid material continuously grows as it gives up heat of fusion. Since this solid layer generally has low thermal conductivity as it grows, heat transfer is impeded, and in turn increases the energy release times. Since convection is a more effective mechanism for heat transfer than conduction, it is easier to supply energy for the melting process than to withdraw energy during solidification. Hence the variation of surface heat flux depends on the predominance of the convective resistance (fixed resistance) and the conductive resistance (variable resistance). When the convective resistance is dominant nearly uniform surface heat flux with time can be achieved from the LHTS system and if the conductive resistance is dominant the surface heat flux will have a decreasing trend with respect to time. Internal heat transfer in PCM storages can be enhanced with fins, metal honeycombs, metal matrices (wire mesh), rings, high conductivity particles, metal fibers or graphite, etc. Moreover, volume change during phase change further complicates the system design.

Table 5
Heat transfer studies in packed bed storage systems

Sl. no.	References	Geometry	Storage medium	HTF	Mode of operation	Range of parameters	Remarks
1.	Benmansour et al. [23]	Spherical capsules inside a cylindrical tank	Paraffin wax	Air	Both charging and discharging	$560 < Re < 1120$; $T_{h,in}$: 70 °C; $T_{c,in}$: ambient; d_c: 31.8 mm; ε: 0.4056	Experimental investigation/ mathematical modelling
2.	Kousksou et al. [24]	Spherical capsules inside a cylindrical tank	Water/ice	Chilled glycol	Charging	$1 < \dot{m}_f < 2.5\,m^3/h$; $T_{initial}$: 6 °C; $-8 < T_{c,in} < -3.5$; d_c: 77 mm; ε: 0.5	Experimental investigation/ mathematical modeling
3.	Arkar and Medved [25]	Spherical capsules inside a cylindrical tank	Paraffin (RT20)	Air	Both charging and discharging	$50 < \dot{m}_f < 220\,m^3/h$; $T_{h,in}$: 35 °C; $T_{c,in}$: 10 °C; d_c: 50 mm; ε: 0.388	Mathematical modelling
4.	Wei et al. [26]	Capsules inside a rectangular tank	Paraffin wax (FNP-0090)	Water	Discharging	$5 < \dot{m}_f < 20$ lpm; $40 < T_{initial} < 105$ °C; $15 < T_{c,in} < 35$ °C; $2 < d_c < 5$ mm; $0.25 < \varepsilon < 0.5$	Experimental investigation/ mathematical modeling
5.	Seeniraj and Lakshmi Narasimhan [27]	Spherical capsules inside a cylindrical tank	–	–	Charging	$1.8 < St < 4$; $0.19 < Ste < 0.32$; $7833 < Pe < 13949$; $0.365 < \varepsilon < 0.65$	Mathematical modelling
6.	Ismail and Henriquez [28]	Spherical capsules inside a cylindrical tank	Water/ice	30% Ethylene glycol + water	Charging	$0.5 < \dot{m}_f < 1.5\,m^3/h$; $T_{initial}$: 20 °C; $-15 < T_{c,in} < -3$ °C; d_c: 77 mm	Experimental investigation/ mathematical modeling
7.	Cho and Choi [29]	Spherical capsules inside a cylindrical tank	*n*-Tetradecane, *n*-tetradecane (40%) + *n*-hexadecane (60%), water	40% ethylene glycol + water	Both charging and discharging	$8 < Re < 16$; $T_{initial}$: 10 °C (discharging); $-7 < T_{initial} < -1$ °C (charging); $T_{h,in}$: 10 °C; $-7 < T_{c,in} < -1$ °C; d_c: 24.5 mm; ε: 0.47	Experimental investigation
8.	Ismail and Stuginsky [30]	Particles inside a cylindrical tank	Stone, steel	Water, air	Both charging and discharging	$0.5 < \dot{m}_f < 1$ kg/s; $25 < d_c < 50$ mm; $0.3 < \varepsilon < 0.5$	Mathematical modelling
9.	Jotshi et al. [31]	Spherical capsules inside a cylindrical tank	Ammonium alum/ Ammonium nitrate eutectic	Air	Discharging	$491 < Re < 531$; $T_{initial}$: 65 °C; $T_{c,in}$: 25 °C; d_c: 25.4 mm; ε: 0.61	Experimental investigation

Table 5 (*continued*)

Sl. no.	References	Geometry	Storage medium	HTF	Mode of operation	Range of parameters	Remarks
10.	Adebiyi et al. [32]	Cylindrical pellets in a cylindrical tank	Zirconium oxide, copper	Flue gas, air	Both charging and discharging	$200<\dot{m}_f<600$ kg/h; $T_{initial}$: 27 °C; $627<T_{h,in}<1127$ °C; $T_{c,in}$: ambient; d_c: 18.3 mm; ε: 0.33	Experimental investigation/ mathematical modeling
11.	Bedecarrats et al. [33]	Spherical capsules in a cylindrical tank	Water/ice	Chilled glycol	Both charging and discharging	$0.9<\dot{m}_f<1.4\,m^3/h$; $T_{initial}$: −6 °C; $5<T_{h,in}<10$ °C; $T_{c,in}$: −6 °C; d_c: 77 mm; ε: 0.38	Experimental investigation/ mathematical modeling
12.	Watanabe and Kanzawa [34]; Watanabe et al. [35]	Cylindrical capsules in a rectangular tank	PCM (Kanto Chemical Co, Japan)	Water	Both charging and discharging	$0.5<\dot{m}_f<1.5$ lpm; $T_{initial}$: 25 °C; $65<T_{h,in}<85$ °C; $25<T_{c,in}<35$ °C; $16<d_c<25$ mm, length:150 mm	Experimental investigation/ mathematical modeling
13.	Goncalves and Probert [36]	Cylindrical cans in a cylindrical tank	$MgCl_2\ 6H_2O$	Water	Both charging and discharging	$50<Re<1600$; $0.927<Ste<1.471$; d_c: 53.2 mm, length: 70 mm; ε: 0.144	Experimental investigation/ mathematical modeling
14.	Chen [37]; Chen and Yue [38]	Spherical capsules in a cylindrical tank	Water/ice	Alcohol	Charging	$2<\dot{m}_f<5$ lpm; $-20<T_{c,in}<-10$ °C; d_c: 34 mm; $0.365<\varepsilon<0.61$	Experimental investigation/ mathematical modeling
15.	Adebiyi [39]	Cylindrical capsules in a cylindrical tank	PCM (IGT)	Flue gas, air	Both charging and discharging	$\dot{m}_f$: 0.59 kg/s; $T_{h,in}$: 1500 K; $T_{c,in}$: 300K; d_c: 25.4 mm (aspect ratio: 1); ε: 0.3	Mathematical modelling
16.	Farid and Husian [40]	Cylindrical tubes in a horizontal rectangular duct	Commercial paraffin wax	Air	Both charging and discharging	$0.007<\dot{m}_f<0.014$ kg/s; $28<T_{initial}<70$ °C; $T_{h,in}$: 75 °C; $T_{c,in}$: 25 °C; d_c: 31.8 mm (length: 335 mm)	Experimental investigation/ mathematical modeling
17.	Arnold [41]	Spherical capsules in a cylindrical tank	Water/ice	Glycol + water	Both charging and discharging	$5<T_{h,in}<10$ °C; $T_{c,in}$: −26 °C; d_c: 105 mm	Mathematical modelling
18.	Laybourn [42]	Rectangular containers in a cylindrical tank	De-ionized water	10% Glycol + water	Both charging and discharging	$\dot{m}_f$: 436 m^3/h; $T_{h,in}$: 12.8 °C; $T_{c,in}$: −6.7 °C; ε: 0.15	Mathematical modelling

Table 6
Heat transfer studies in capsules of various geometry

Sl. no.	References	Geometry	Boundary condition	Storage medium	HTF	Mode of operation	Range of parameters	Remarks
1.	Chan and Tan [43]	Spherical enclosure	Constant temperature	*n*-Hexadecane	Water	Solidification	$3<T_c<13\,^{\circ}C$; $0<T_{initial}$ (super heat) $<9\,^{\circ}C$	Experimental investigation
2.	Ettouney [44]	Spherical shell	Convective	Paraffin wax	Air	Both melting and solidification	$4<\dot{m}_f<10$ m/s; $T_{initial}$: ambient (during charging), $60<T_{initial}<90\,^{\circ}C$ (during discharging); $60<T_h<90\,^{\circ}C$; T_c: $24\,^{\circ}C$; $20<d_c<60$ mm	Experimental investigation
3.	Bilir and Ilken [45]	Cylindrical/ spherical containers	Convective	Water	–	Solidification	$0.01<Ste<0.5$; $0.2<$ super heat <1; $1<Bi<50$	Mathematical modelling
4.	Shiina and Inagaki [46]	Cylindrical capsule	Convective	Water, Octadecane, Li_2CO_3, NaCl	Water, helium, air	Melting	$300<Re<7500$; $T_{initial}$: T_m–$5\,^{\circ}C$; T_h: $T_m+5\,^{\circ}C$; $6<d_c<10$ mm	Experimental investigation and mathematical modelling
5.	Koizumi [47]	Spherical capsule	Convective	*n*-Octadecane	Air	Melting	$150<Re<1800$; $T_{initial}$: 298 K; T_h: 321 K; d_c: 50 mm	Experimental investigation
6.	Barba and Spiga [48]	Slab, cylinder or spherical capsules	Constant temperature	Eutectic mixture of hydrate nitrates of ammonium and magnesium	–	Solidification	$0.25<Ja<2$	Mathematical modelling
7.	Lin and Jiang [49]	Plate, cylinder or spherical capsules	Constant temperature	–	–	Solidification	$0.05<Ste<2$	Mathematical modelling
8.	Ismail and Henriquez [50,51]	Spherical capsule	Convective	Water/ice	Ethanol	Solidification	$5<T_{initial}<35\,^{\circ}C$; $-25<T_c<-5\,^{\circ}C$; $10<d_c<200$ mm	Mathematical modelling
9.	Eames and Adref [52]	Spherical enclosure	Convective	Water/ice	Chilled water	Both melting and solidification	$\dot{m}_f$: 0.1 m/s; $4.5<T_h<12\,^{\circ}C$; $-9.5<T_c<-4.4\,^{\circ}C$; $62.7<d_c<81.4$ mm	Experimental investigation

Table 6 (*continued*)

Sl. no.	References	Geometry	Boundary condition	Storage medium	HTF	Mode of operation	Range of parameters	Remarks
10.	Fomin et al. [53]	Elliptic capsule	Constant temperature	*n*-Octadecane	–	Melting	$T_{initial}$: T_m; Ste: 0.1; 0.2 < Aspect ratio < 5	Mathematical modelling
11.	Wilchinsky et al. [54]	Elastic spherical and cylindrical capsule	Constant temperature	Paraffin	–	Melting	$T_{initial}$: T_m; Ste: 0.1	Mathematical modelling
12.	Silva et al. [55]	Vertical rectangular enclosure	Constant-rate heating on one of wall during charging, an airflow stream during discharging	Paraffin wax	Air (during discharging)	Both melting and solidification	$\dot{m}_f$: 0.005488 kg/s; q: 480 W/m^2; T_c: 19.3 °C; height: 813 mm; length: 623 mm	Experimental investigation and Mathematical modelling
13.	Khodadadi and Zhang [56]	Spherical container	Constant temperature	Paraffin wax	–	Melting	$T_{initial}$: ambient; 0.008 < Ste < 0.0533; 20 < d_c < 100 mm	Mathematical modelling
14.	Zivkovic and Fujii [57]	Rectangular and cylindrical containers	Convective	$CaCl_2$ $6H_2O$	Air	Melting	$T_{initial}$: 15 °C; T_h: 60 °C; 5 < d_c < 20 mm	Mathematical modelling
15.	Saito et al. [58]	Cylindrical capsule	Convective	Gelled sodium sulfate decahydrate	Water	Solidification	5×10^{-4} < cooling rate < 1.6×10^{-3}; 26 < $T_{initial}$ < 34 °C; d_c: 24.3 mm, length: 1220 mm	Experimental investigation and Mathematical modeling
16.	Lacroix [59]	Parallelepedic capsule	Constant temperature at the top and bottom surfaces and side walls adiabatic	*n*-Octadecane	–	Melting	0 < sub cool parameter < 5; 0.00926 < Ste < 0.0926; length: 75 mm, 25 < width < 225, height: 30 mm	Mathematical modelling
17.	Fomin and Saitoh [60]	Spherical capsule	Convective	–	–	Melting	–	Mathematical modelling
18.	Yagi and Akiyama [61]	Spherical capsule	Convective	Al, NaCl, KNO_3, Pb, Al-12, Al-25	Nitrogen gas	Both melting and solidification	2.33 < $\dot{m}_f$ < 4.67×10^{-3} m^3/s; 573 < T_h < 1173 K; T_c : 298 K; d_c: 40 mm	Experimental investigation and Mathematical modelling

19.	Hirata et al. [62]	Horizontal rectangular capsule	Constant temperature	Ice, octadecane	–	Melting	$T_{initial}$: (T_m–2) °C; 0.0287 < Ste < 0.251; 1/3 < aspect ratio < 3	Experimental investigation and Mathematical modelling
20.	Himeno et al. [63]	Horizontal cylinder	Convective	Binary mixture of *p*-dichloro-benzene and *p*-dibromo-benzene	Silicon oil	Melting	d_c: 36 mm	Experimental investigation
21.	Rieger and Beer [64]	Horizontal cylinder	Constant temperature	Ice	–	Melting	$T_{initial}$: T_m; 4 < T_h < 15 °C	Mathematical modelling
22.	Sparrow and Myrum [65]	Circular tube with various inclination angles	Convective	*n*-Eicosane	Water	Melting	0.041 < Ste < 0.25; d_c: 50.8 mm, length: 394 mm	Experimental investigation
23.	Bareiss and Beer [66]	Horizontal tube	Convective	*n*-Octadecane, *p*-xylene	Water	Melting	$T_{initial}$: T_m–0.5 °C; 0.05 < Ste < 0.18; 16 < d_c < 30 mm	Experimental investigation and Mathematical modelling
24.	Rieger et al. [67]	Horizontal cylinder	Constant temperature	*n*-Octadecane	Water	Melting	$T_{initial}$: T_m; 0.01 < Ste < 0.1; d_c: 32 mm, length: 40 mm	Experimental investigation and mathematical modelling
25.	Katayama et al. [68]	Horizontal cylindrical capsule	Constant temperature	Naphthalene	Water	Both melting and solidification	86 < T_h < 99.5°C; 63 < T_c < 73 °C; d_c: 40 mm, length: 300 mm	Experimental investigation and mathematical modelling

In general, the heat transfer analysis of phase change problem is much more complex than single phase problems owing to: (1) non-linearity of the problem resulting from the motion of the solid–liquid interface during phase change; (2) inadequate knowledge of the heat transfer process at the solid–liquid interface because of buoyancy driven natural convection in the liquid; (3) uncertainty of the interface thermal resistance between the container and the solid PCM; (4) volume change with change of phase (upon shrinkage); and (5) the presence and configuration of voids in a solid.

In order to solve the phase change problem several methodologies have been reported in the literature based on the theoretical and experimental investigations. There are five important methods, namely, (i) fixed grid methods, (ii) variable grid methods, (iii) front fixing method, (iv) adaptive grid generation method and (v) Enthalpy method. Table 6 presents the summary of salient features of the studies carried out on phase change process of PCM inside the capsules.

6. Applications

Table 7 lists some of the different applications found in the literature. These applications can be divided into two main groups: thermal protection or inertia, and storage. One difference between these two substantial fields of application relates to the thermal conductivity of the substance. In some cases of thermal protection it is appropriate to have low conductivity values, while in storage systems such low values can produce a real problem since there can be sufficient energy stored but insufficient capacity to dispose of this energy quickly enough.

7. New PCM technological innovations

Revankar [69] has devised a new method for satellite power testing using PCMs. Central to the solar power system are series of metal cells which contain a PCM that is liquid under high temperature, which then freezes during hours of cold darkness, releasing its latent heat. The heat released can then be used to generate electricity by driving thermoelectric units. Because the systems generate at least three times more power than batteries of

Table 7
PCM-TES applications

Sl. no.	Application
1	Thermal storage of solar energy
2	Passive storage in bioclimatic building/architecture
3	Cooling: use of off-peak rates and reduction of installed power, icebank
4	Heating and sanitary hot water: using off-peak rate and adapting unloading curves
5	Thermal protection of food: transport, hotel trade, ice-cream, etc.
6	Thermal protection of electronic devices (integrated in the appliance)
7	Medical applications: transport of blood, operating tables, hot and cold therapies
8	Cooling of engines (electric and combustion)
9	Thermal comfort in vehicles
10	Solar power plants

comparable size, they are seen as a possible alternative to conventional satellite solar power systems that rely on batteries. By having a hot converter at the start of a trip, auto emissions, such as hydrocarbons and carbon monoxide, can be reduced dramatically by up to 80%. National Renewable Energy Laboratory (NREL) wrapped its catalytic converter in compact vacuum insulation to keep it at an efficient operating temperature for up to 24 h after the engine is shut off. A catalytic converter was developed by using PCMs to absorb, store and release heat as needed. John et al. [70] have designed a novel ventilation nighttime cooling system (a novel combination of PCM and heat pipes) as an alternative to air conditioning. The system offers substantial benefits in terms of reducing or eliminating the need for air conditioning and thereby significantly reducing CO_2 emissions and saving energy in buildings. Particles of microencapsulated PCM (3–100 μm) and/or macroencapsulated PCM (1–3 mm) can be included within textile fibers, composites, and clothing to provide greatly enhanced thermal protection in both hot and cold environments.

8. Conclusions

A review of TES using solid–liquid phase change has been carried out. The information obtained is presented by dividing the section into six parts: materials, encapsulation, design, heat transfer studies, applications and new PCM technology innovation. The summary of salient features of the investigations carried out in the area of heat transfer characteristics of packed bed latent heat thermal energy storage system and PCM capsule is also distinguished.

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